

B. BUECKER, ChemTreat, Lawrence, Kansas;
and R. AULL, Richard Aull Consulting,
Reading, Pennsylvania

Cooling tower heat transfer basics—Part 3

Refineries, chemical plants and numerous other industrial facilities utilize open recirculating cooling systems equipped with cooling towers for cooling in scores of heat exchangers. With the turnover that is occurring in nearly all industries due to the retirement of Baby Boomers, many new personnel are being introduced to cooling tower technology. This article outlines the fundamentals of heat transfer in a cooling tower and illustrates why the chemistry principles outlined in Parts 1 and 2—published in the June and July issues of *Hydrocarbon Processing*—are critical for maintaining cooling tower efficiency and structural integrity.

Psychrometry and heat transfer. In the words of an excellent reference manual on cooling, “Evaporation is utilized to its fullest extent in cooling towers, which are designed to expose the maximum transient water surface to the maximum flow of air—for the longest period of time.”¹ Evaporation is the key to maximizing efficiency. For water to evaporate, it must consume a large amount of energy to change from a liquid to a gas. This is known as the latent heat of vaporization, which, at sea level, is typically around 1,000 Btu/lb. Cooling towers remove a very large amount of heat, primarily from the evaporation of a small amount of the recirculating water (FIG. 1).

An important concept for understanding cooling tower heat transfer is that of wet bulb (WB) temperature. Consider being outdoors—in the shade—on a 90°F (32°C) day at 40% relative humidity. A standard thermometer would naturally read 90°F, which is the dry bulb (DB) temperature. Imagine that we place another thermometer attached alongside the DB thermometer but have placed a soaked piece of cloth around the bulb of

the other thermometer and have both on a swivel such that the thermometers can be swirled very rapidly through the air. This instrument is known as a sling psychrometer (FIG. 2).

After a short time, the DB thermometer will still read 90°F; however, the other thermometer will read 71.2°F (21.8°C).² This latter reading is the WB temperature, and it is the lowest temperature that can be achieved by evaporative cooling. Modern psychrometers are mechanically aspirated (fans move the air across the wetted wick) and are much more accurate.

No matter how efficient, a cooling tower can never chill the recirculating water to the WB temperature, and, at some point, costs and space requirements limit cooling tower size. The separation in temperature between the chilled water and WB value is known as the “approach” temperature. The closest approach temperature that can be reached with a modern tower—economically—is about 4°F (–15.5°C), with a typical range being 10°F (–12.2°C). The range is the difference between the temperature of the water entering the tower compared to that

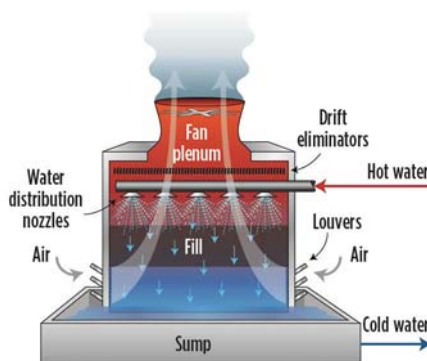


FIG. 1. General outline of a mechanical counterflow cooling tower.



FIG. 2. Picture of a vintage sling psychrometer.

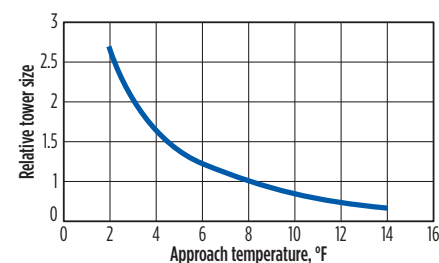


FIG. 3. Chart of relative cooling tower sizes vs. approach temperatures for general applications.

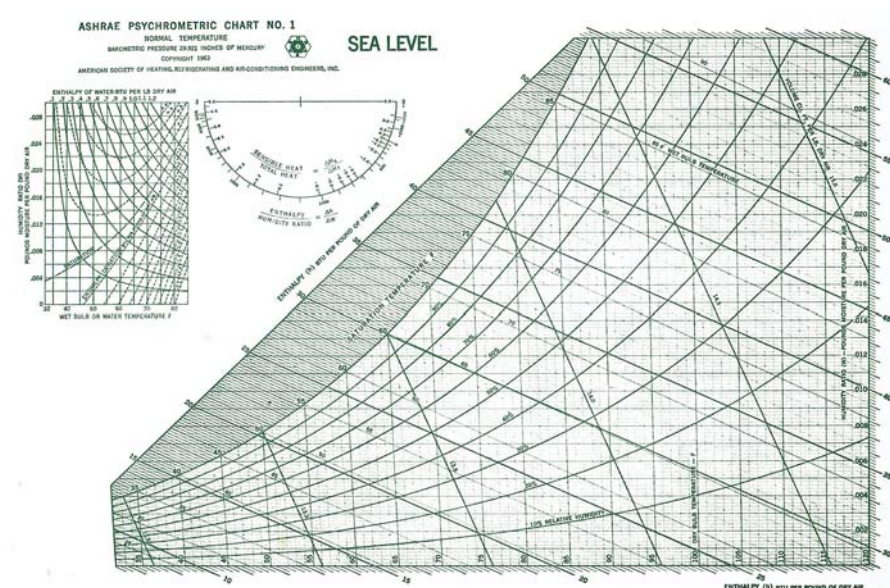


FIG. 4. A standard psychrometric chart for sea-level elevation. Chart courtesy of the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE).

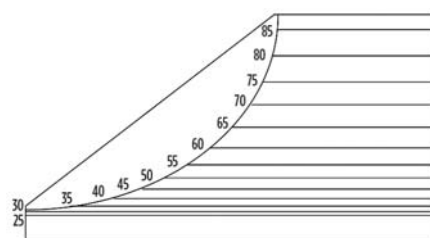


FIG. 5. Dewpoint (°F) temperature on a psychrometric chart (not to scale).

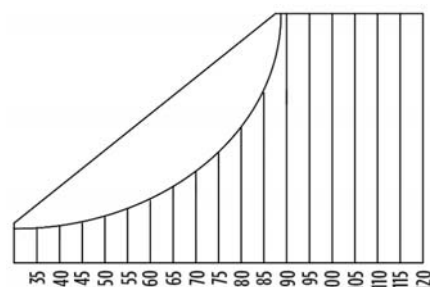


FIG. 6. Dry bulb temperature (°F) on a psychrometric chart (not to scale).

leaving the tower. FIG. 3 shows the cooling tower size vs. the approach temperature for general applications.

The data needed to calculate heat transfer by air cooling and evaporation has been compiled in a graph known as a psychrometric chart (FIG. 4). At first glance, the chart appears to be complicated. However, the following explains how to read it.

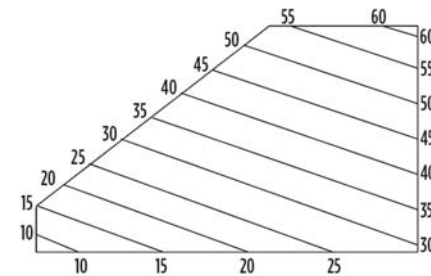


FIG. 7. Enthalpy (Btu/lb of dry air) section of a psychrometric chart (not to scale).

Reading a psychrometric chart. A psychrometric chart is filled with data that can sometimes be difficult to follow. Psychrometric programs are now available online, where data can be plugged in to find any other value. Learning how to read a psychrometric chart remains valuable for fully understanding the process.

FIGS. 5-11 break out each of the parameters and illustrate how to find the value of interest from a standard psychrometric chart. FIG. 5 shows dewpoint (dp) temperature. The dp temperature is the temperature to which the air would need to be cooled for water vapor to begin condensing.

DB temperature is the actual air temperature (FIG. 6). For example, 80°F (26.7°C) at 10% relative humidity has the same DB temperature as 80°F (26.7°C) at 60% relative humidity, although conditions would not feel the same to a person jogging or working outdoors.

Enthalpy (H) is the energy content of the fluid (FIG. 7). It is one of the most important concepts of thermodynamics and is critical for heat transfer and work calculations.

Humidity ratio (W) is the absolute value of moisture in air, as differentiated from relative humidity (FIG. 8). In a later section of this article, an example calculation illustrates the importance of this data.

Relative humidity (RH) is the amount of moisture in the air (i.e., %), as compared to the maximum amount that the air can hold at that temperature (FIG. 9). A drop in temperature, with no other changes, will cause the relative humidity to rise, which is also equivalent to approaching the dewpoint. Likewise, an increase in temperature, with no other changes, will cause the relative humidity to decrease.

Specific volume (V) is the air volume per a specific weight, most commonly ft³/lb of dry air (FIG. 10). Air expands and contracts with temperature, and it changes weight as it adsorbs or desorbs moisture. Specific volume is important in sizing fans, blowers and other air handling equipment.

WB temperature (FIG. 11) is the lowest theoretical temperature to which water can be cooled by evaporation. The WB temperature is determined in the field by a psychrometer. A cooling tower, no matter how large, can never cool to the WB temperature.

The following section describes how the chart works. Consider ambient air at 90°F (32.2°C) and 40% relative humidity. These two properties are easily measurable with common instruments. Within the psychrometric chart, find the 90°F (32.2°C) DB temperature and then follow this line vertically until it intersects with the curved 40% relative humidity line. All other parameters can be determined:

- W is found by moving horizontally from the 90°F, 40% RH point to the W scale on the right. In this case, W is 0.0122 lb of moisture per pound of dry air.
- For WB temperature, follow the diagonal line to the WB scale on the curve. For this example, the WB temperature is 71.2°F (21.8°C).
- Dp is another horizontal line graph, with the scale located on the curve (except at low temperature). In this case, dp temperature is 63.8°F (17.7°C).

- H is another set of diagonal lines that closely match the slope of the WB graph. However, the H scale is located on the diagonal border of the psychrometric chart. H for 90°F air at 40% RH is 35.1 Btu/lb.
- V is another diagonal graph, where the scale is located within the chart and not necessarily also at the boundaries. In this example, V is 14.2 ft³/lb.

A limitation with the hard copy is that all values are calculated at sea level. Obviously, most towers do not sit at sea level, so the data can be slightly to significantly inaccurate depending on tower location. However, in this era of modern computer technology, programs are available that will provide the calculations for virtually any scenario.

A practical example of cooling tower heat transfer. The following practical example outlines how heat is transferred in a cooling tower. FIG. 12 shows process conditions that could easily exist in a cooling system. The following will show how to calculate the mass flowrate of air needed to cool 150,000 gal/min of tower inlet water to the desired temperature, as well as the water lost by evaporation.

The first step is to determine the energy balance around the tower (Eq. 1):³

$$(\dot{m}_{a1} \times h_{a1}) + (\dot{m}_{w3} \times h_{w3}) = (\dot{m}_{a2} \times h_{a2}) + (\dot{m}_{w4} \times h_{w4}) \quad (1)$$

where:

$\dot{m}_a$ = Mass flowrate of dry air
 h_a = Enthalpy of dry air streams
 h_w = Enthalpy of water streams.

Utilizing algebra, the fact that $\dot{m}_{a1} = \dot{m}_{a2}$ and that a mass balance on the water flow is $\dot{m}_4 = \dot{m}_3 - (W_2 - W_1) \times \dot{m}_a$, where W = humidity ratio, the energy balance equation can be rewritten as Eq. 2:

$$\dot{m}_a = (\dot{m}_3 \times (h_4 - h_3)) / [((h_1 - h_2) + (W_2 - W_1) \times h_4)] \quad (2)$$

Using toolkit software from the Cooling Technology Institute for the air component and the steam tables for the circulating water, the following is found:

- $h_1 = 24.3$ Btu/lb/min
- $h_2 = 52.6$ Btu/lb/min
- $h_3 = 72.0$ Btu/lb/min
- $h_4 = 45.1$ Btu/lb/min

- $W_1 = 0.0073$ lb of moisture per lb of dry air
- $W_2 = 0.0286$ lb of moisture per lb of dry air.

With an inlet cooling water flowrate of 150,000 gal/min (1,242,000 lb/min with water at 104°F/40°C and having a density of 8.28 lb/gal), the calculated air flow is 1,222,040 lb/min, which is close to the cooling water flowrate. Obviously, the air flow requirement would change significantly depending on air temperature, inlet water temperature and flowrate, and other factors. That is why

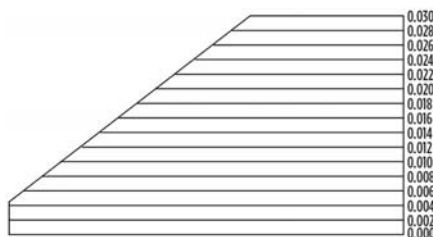


FIG. 8. Humidity ratio (lb of moisture per lb of dry air) on a psychrometric chart (not to scale).

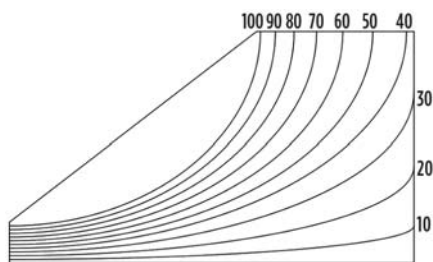


FIG. 9. Relative humidity (%) on a psychrometric chart (not to scale).

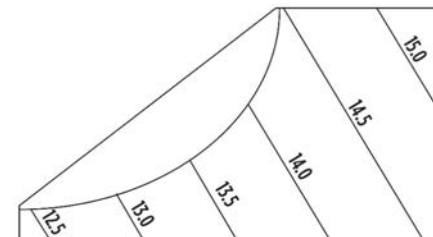


FIG. 10. Specific volume (ft³/lb of dry air) on a psychrometric chart (not to scale).

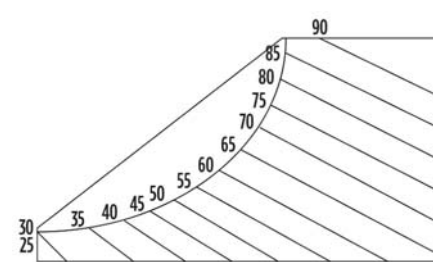


FIG. 11. WB temperature (°F) on a psychrometric chart (not to scale).

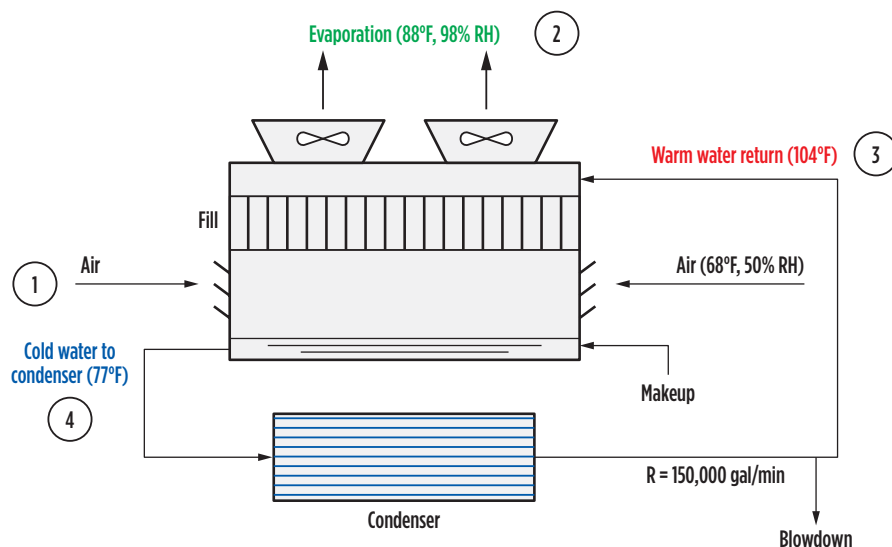


FIG. 12. A cooling tower water and air flow example.

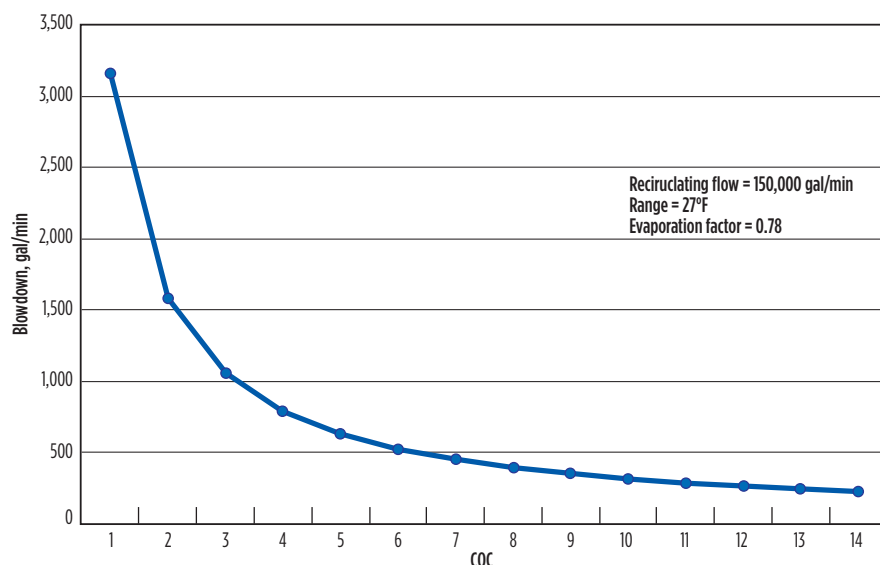


FIG. 13. COC vs. blowdown for the cooling tower example shown in FIG. 3.



FIG. 14. A modern splash fill arrangement. Source: Brentwood Industries.

Utilizing the data, $\dot{m}_4 = 146,856$ gal/min. Therefore, the water lost to evaporation is:

$$\dot{m}_3 - \dot{m}_4 = 3,144 \text{ gal/min}$$

The important aspect of this example is that only about 2% evaporation is enough to provide most of the cooling.

Quick calculations. For a quicker evaluation of cooling tower evaporation, a simpler equation is available (Eq. 4):

$$E = (f \times R \times \Delta T) / 1,000 \quad (4)$$

where:

E = Evaporation in gal/min

R = Recirculation rate in gal/min

ΔT = Temperature difference (range)

between the warm and cooled circulating water ($^{\circ}\text{F}$)

f = A correction factor that helps account for sensible heat transfer, where f (average) is often considered to be 0.75–0.8 but will rise in summer and decline in winter.

The factor of 1,000 is the approximate latent heat of vaporization (Btu/lb) that was outlined previously. To check the general accuracy of this calculation, consider the previous problem. Evaporation was 3,144 gal/min, with a recirculation rate of 150,000 gal/min and a temperature range of 27°F (-2.8°C). Use of this general data gives a correction factor of 0.78, which fits in perfectly with the typical range for normal operation.

Evaporation causes dissolved and suspended solids in the cooling water to increase in concentration. This concentration factor is (logically) termed the *cycles of concentration* (COC). COC—perhaps more accurately called “allowable COC”—varies from tower to tower depending on many factors, including makeup water chemistry and quality, heat load, effectiveness of chemical treatment programs and restrictions on water discharge (FIG. 13).

COC can be monitored by comparing the ratio of the concentration of a soluble ion, such as chloride, in the makeup (MU) and recirculating water. Very common is a comparison of the specific conductivity of the two streams, particularly where automatic control is utilized to bleed off recirculating water when it

becomes too concentrated. A common range for COC in many towers is 4–6, as water savings via bleed off—also known as blowdown (BD)—beyond this range become minimal, as FIG. 13 shows. In very arid locations, COC may need to be high, but chemistry control and monitoring become more important and difficult.

Besides BD, some water also escapes the process as fine moisture droplets in the cooling tower fan exhaust. This water loss is known as drift (D). In towers with state-of-the-art drift eliminators, drift is quite small and can be at or below 0.0005% of the recirculation rate. Leaks in the cooling system are referred to as losses (L). Eqs. 5–7 show relationships between evaporation, blowdown, make-up, losses and COC in a cooling tower as based on flowrates:

$$\text{COC} = \text{MU} / \text{BD} \quad (5)$$

$$\text{MU} = E + \text{BD} + D + L \quad (6)$$

$$\text{BD} = E / (\text{COC} - 1) \quad (7)$$

Ensuring good tower efficiency. The heart of a cooling tower is the fill. This is the internal material that enhances air-water contact. The type of fill utilized in early cooling towers was splash fill made of wooden slats placed in a staggered formation. As the cooling water cascaded down and onto wooden slats, large droplets broke into smaller droplets to increase the water surface area. Splash fill technology has considerably improved, and a modern design is shown in FIG. 14.

Splash fill is commonly utilized in crossflow cooling towers where the air travels perpendicularly to the water spray. Splash fill may also be necessary in cooling towers where the water has a high fouling tendency.

In most towers, film fill is the preferred material. A guiding principle behind film fill design and selection is to increase air-to-water contact. Typical fills are made of PVC because of its low cost, durability, good wetting characteristics and inherently low flame spread rate. One might be tempted to think that film fill is generic in nature and that any type can be installed in a tower. However, that is not the case. The choices of fill flow path and the space between the fill sheets (flute size) must be evaluated carefully and are dependent on the projected quality of the water that will be flowing through the tower. FIGS. 15A–15D detail several film fill styles ranging from a

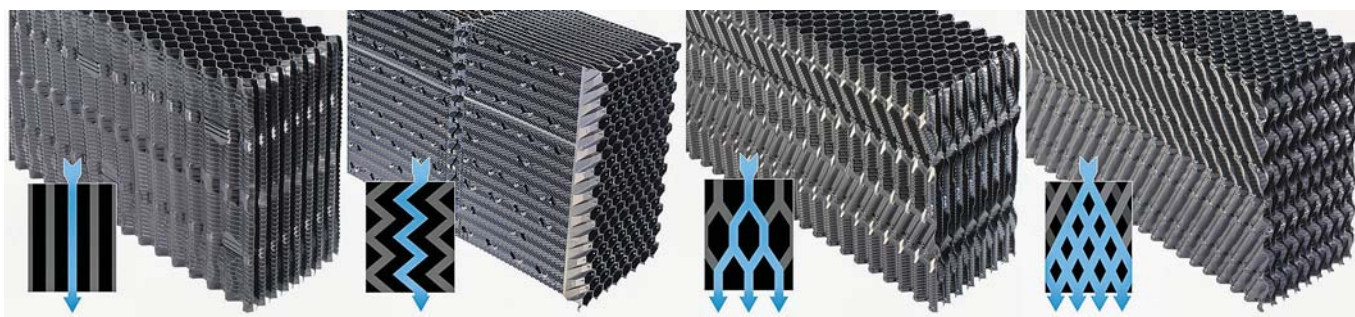


FIG. 15. Several film fill styles: (a) vertical flutes, (b) XF standoff, (c) offset flutes and (d) cross flutes. Source: Brentwood Industries.

low-fouling design for waters high in suspended solids and/or fouling potential to that of the highest efficiency.

The greater the fill efficiency, the more tortuous the flow path. Cooling tower manufacturers continue to improve on these high-efficiency designs. However, high efficiency is a double-edged sword, in that the complex flow path greatly increases potential locations for fouling and accumulation of deposits. Careful selection of fill design and style, in consultation with cooling water experts, is crucial for any new project. Engineering teams cannot specify a tower design without considering water quality factors that can greatly influence performance and operation of the tower.

Another internal component design that has been greatly improved is the mist eliminator. Originally, drift eliminators were made of wood lath, and the number of layers defined the number of passes. In fact, many specifiers still use the phrase “three-pass” drift eliminators to describe modern cellular designs. A more accurate description is the number of directional changes that the droplet-laden air must take.

These cellular designs use the principle of inertial impaction to scrub the drift droplets from the exhaust air. This principle works as such: multiple directional changes force the air to change directions. This creates a tortuous path for the droplets, which, based on mass, collide with the drift eliminator internal surfaces. The droplets form a water film that then cascades back down into the fill. Highly efficient cellular designs can limit drift to 0.0005% and even lower, depending on air velocity (FIG. 16).

Since drift eliminators work by inertial impaction, they lose effectiveness at very low velocities (< 300 ft/min). On

the other end of the spectrum is a phenomenon termed “breakthrough” velocity. This is the velocity that, when exceeded, will cause the water film to tear away from the internal surfaces and become entrained in the exhaust air stream. Highly efficient cellular drift eliminators typically have breakthrough velocities greater than 1,300 ft/min. This is an important consideration for cooling tower designers and specifiers—to manage the tower’s overall design so that high-velocity peaks do not occur in the tower’s plenum and exceed the specified drift eliminator’s breakthrough velocity.

Another complication for designers and specifiers is “compromised” water (e.g., municipal wastewater effluent) that may be used for plant makeup, which may have high concentrations of surfactants. Surfactants have the effect of reducing the water’s surface tension to create smaller droplets. These droplets can then become fluidized within the exit air stream, making a high-efficiency cellular drift eliminator much less effective. Specifiers and end users must evaluate the lowest expected surface tension for design if compromised waters are to be used as makeup. **HP**

LITERATURE CITED

- ¹ Hensley, J. C., *Cooling Tower Fundamentals*, 2nd Edition; SPX Cooling Technologies, 2009.
- ² Swenson, S. D., *HVAC—Heating, Ventilating, and Air Conditioning*, 3rd Edition; American Technical Publishers, Inc.; Homewood, Illinois, 2004.
- ³ Potter, M. C. and C. W. Somerton, *Schaum's Outline of Thermodynamics for Engineers*; McGraw-Hill, New York, New York, 1993.



BRAD BUECKER is a Senior Technical Publicist with ChemTreat. He has many years of experience in or affiliated with the power industry, much of it in steam generation chemistry, water treatment, air quality control and results engineering positions with City Water, Light &

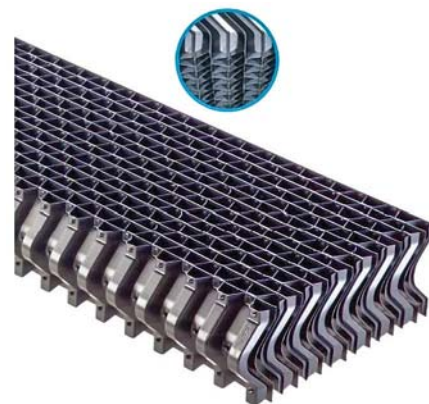


FIG. 16. Drainage tips keep the water film draining, thus reducing pressure drop and increasing drift droplet collection efficiency.

Power (Springfield, Illinois) and Kansas City Power & Light Co. (now Evergy). Mr. Buecker earned a BS degree in chemistry from Iowa State University, with additional course work in fluid mechanics, energy and materials balances and advanced inorganic chemistry. He is a member of the American Chemical Society, American Institute of Chemical Engineers, the American Society of Mechanical Engineers, the Cooling Technology Institute, the National Association of Corrosion Engineers, the Electric Utility Chemistry Workshop planning committee and the International Water Conference Advisory Council. Mr. Buecker has authored many articles and three books on power plant and water/steam chemistry.



RICHARD J. AULL is an Engineering Consultant with more than 40 yr of industry experience in cooling tower thermal design, and performance rating and analysis. Prior to his consulting work, he directed the application engineering and research and development activities for the Cooling Tower Products Group of Brentwood Industries. Prior to joining Brentwood, he held a variety of engineering positions within Research Cottrell's Hamon Cooling Tower Division and Ecodyne's Cooling Tower Services Group, specializing in acquiring and managing cooling tower thermal and structural upgrades, as well as in the testing of cooling towers and the development of cooling tower rating software for in-house use. Mr. Aull earned BS and MS degrees in mechanical engineering from the New Jersey Institute of Technology.